

# Flux Cancellation: The Key to Solar Eruptions

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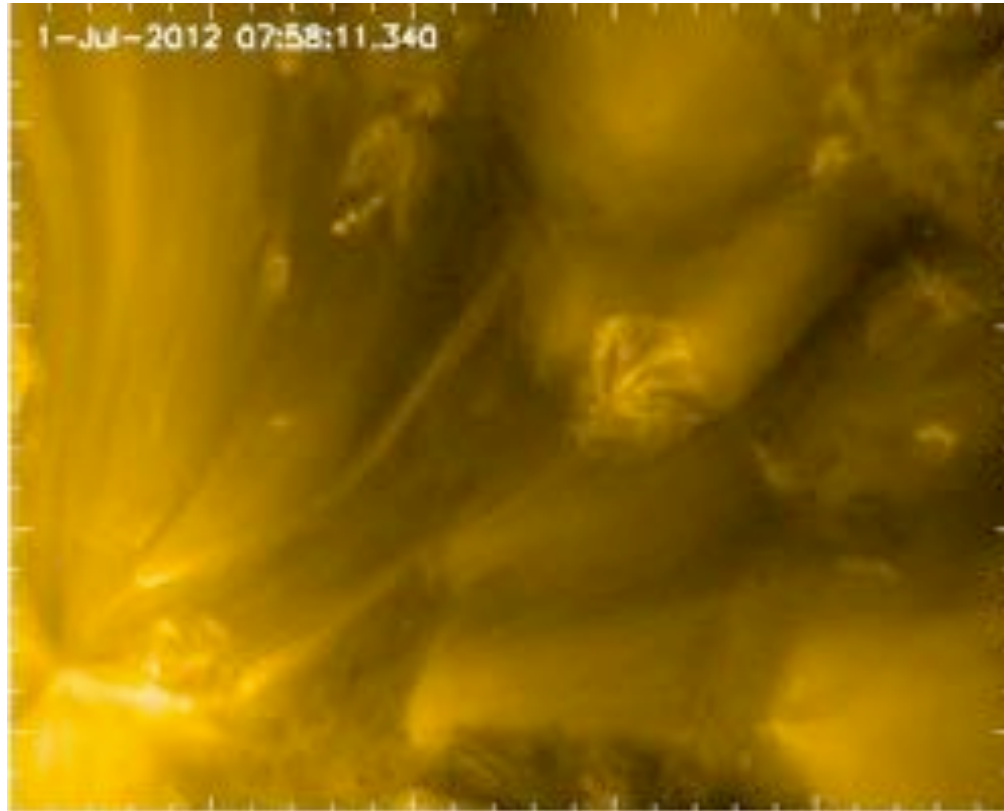


# OUTLINE

- Background
- Triggering of Jet-Driving Minifilament Eruptions
- Formation of Jet-Driving Minifilament Eruptions
- Triggering of CME-producing Filament Eruptions
- Summary



## Background

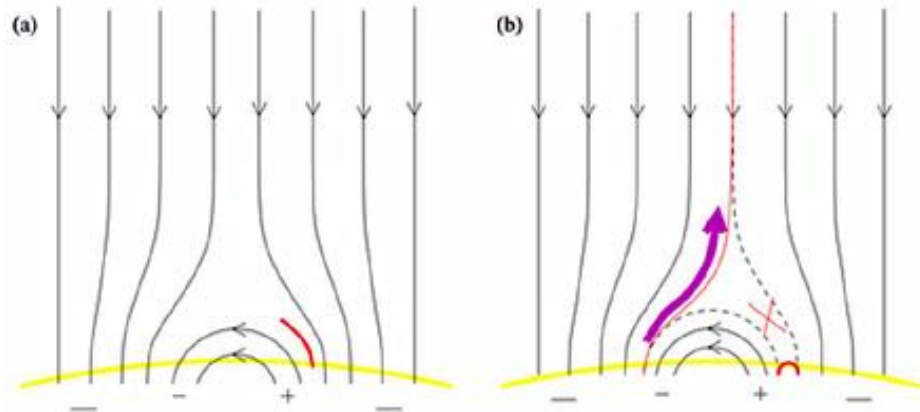


- Coronal jets are frequent magnetically channeled narrow eruptions. They occur in various solar environments: quiet regions, coronal holes and active regions.
- All coronal jets observed in EUV and X-ray images show a bright spire with a base brightening, also known as jet bright point (JBP).

## Solar Jet Models

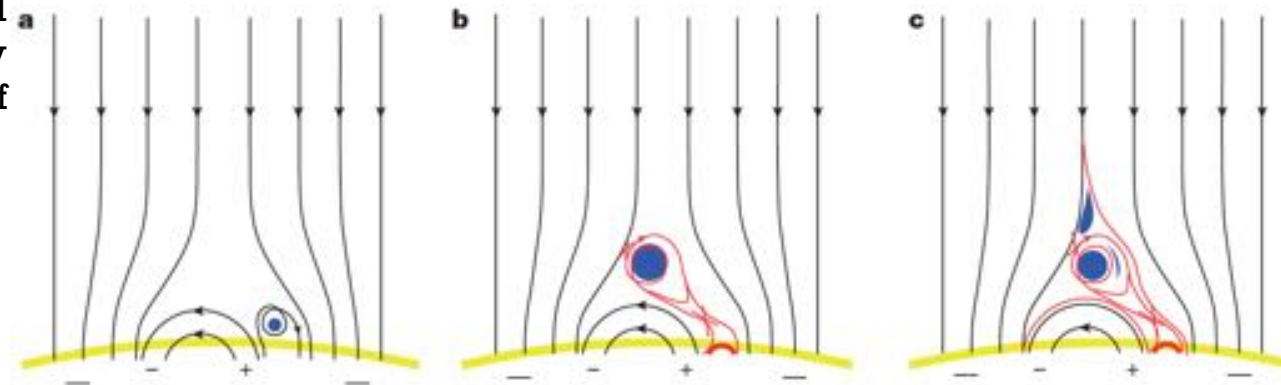
- Some studies have suggested that flux emergence may lead to the jet eruptions (e.g. *Shibata et al. 1992, 2007, Moreno-Insertis et al 2008*).
- Recent studies show that coronal jets are driven by small-scale filament eruptions (e.g. *Hong et al. 2011, Shen et al. 2012, Adams et al. 2014, Sterling et al 2015*).
- Sterling et al. 2015* did an extensive study of 20 polar coronal hole jets and found that X-ray jets are mainly driven by the eruption of minifilaments.
- What leads to these minifilament eruptions?**
- How and when are minifilaments formed?**

Emerging-flux jet model



*Shibata et al 1992, 2007*

Minifilament-eruption jet model



*Sterling et al 2015*

- We examined the magnetic cause of 10 random on-disk quiet region jet eruptions by using SDO/HMI magnetograms and SDO/AIA images.

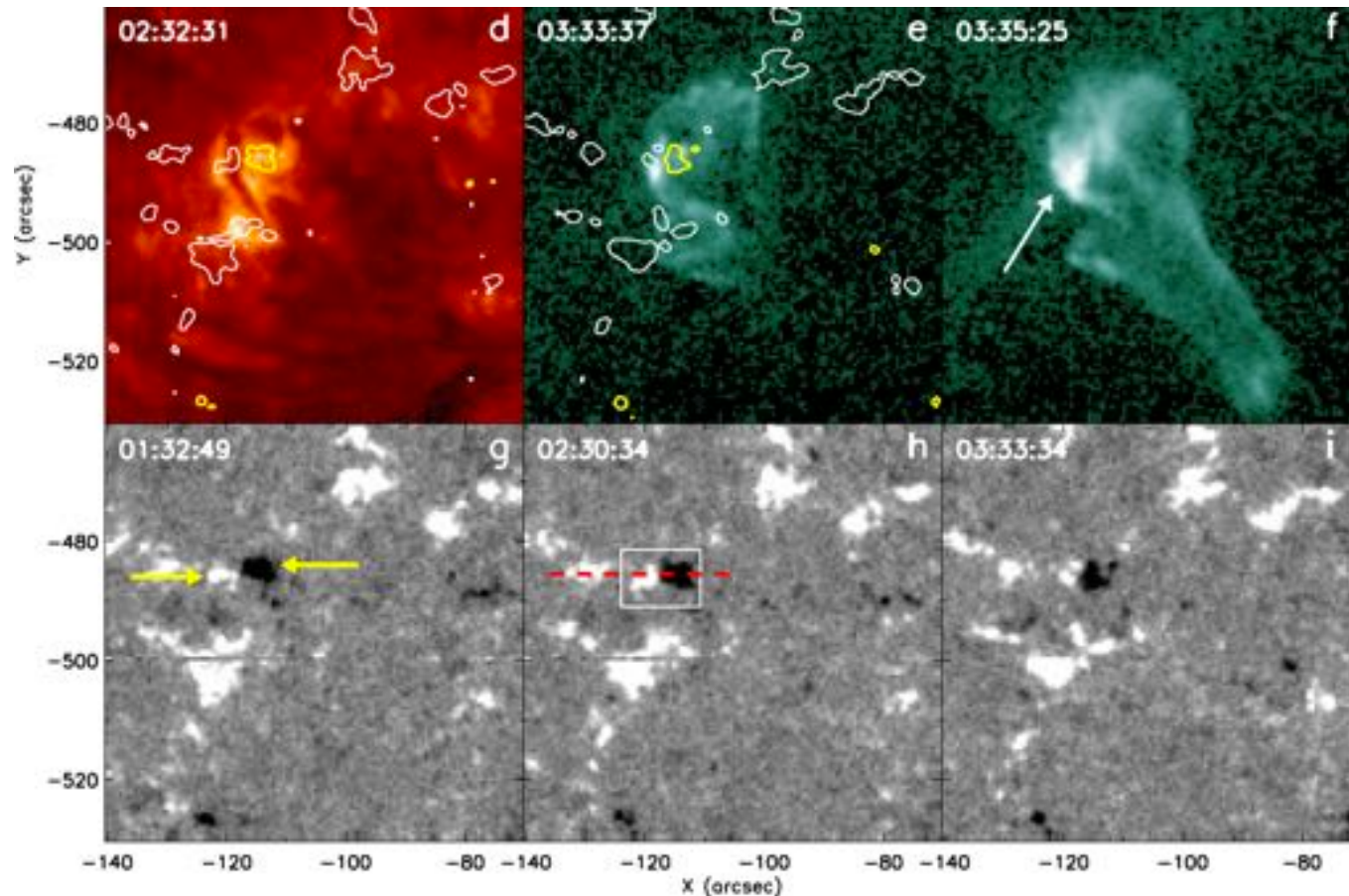
Measured parameters for the observed quiet-region jets:

| Event No. | Date                     | Time <sup>a</sup> (UT) | Location <sup>b</sup> x,y (arcsec) | Jet Speed <sup>c</sup> (km s <sup>-1</sup> ) | Jet Dur. <sup>d</sup> min. | Jet-base <sup>e</sup> Width (km) | Minifil. length <sup>f</sup> ( $\pm 1700$ km) | $\Phi$ values <sup>g</sup> 10 <sup>19</sup> Mx | % of $\Phi^h$ reduction |
|-----------|--------------------------|------------------------|------------------------------------|--|----------------------------|----------------------------------|---|--|-------------------------|
| J1        | 2012 Mar 22              | 04:46                  | -470,-100                          | 100 $\pm$ 30                                 | 15 $\pm$ 5                 | 10500 $\pm$ 500                  | 9800  | 1.6  | 52 $\pm$ 5.8            |
| J2        | 2012 Jul 01              | 08:32                  | -44, 285                           | 100 $\pm$ 10                                 | 10 $\pm$ 2                 | 27000 $\pm$ 500                  | 25000   | 4.0  | 18 $\pm$ 6.8            |
| J3        | 2012 Jul 07              | 21:31                  | -192,-180                          | 120 $\pm$ 15                                 | 14 $\pm$ 3                 | 16500 $\pm$ 400                  | 10500   | — <sup>i</sup>                                 | —                       |
| J4        | 2012 Aug 05 <sup>j</sup> | 02:20                  | -485, 190                          | 140 $\pm$ 35                                 | 10 $\pm$ 3                 | 22000 $\pm$ 1000                 | 31000   | 1.5  | 21 $\pm$ 6.0            |
| J5        | 2012 Aug 10              | 23:03                  | -168,-443                          | 125 $\pm$ 15                                 | 15 $\pm$ 2                 | 16000 $\pm$ 400                  | 10000   | 0.9  | 57 $\pm$ 5.4            |
| J6        | 2012 Sept 20             | 22:56                  | -158,-486                          | 35 $\pm$ 5                                   | 9 $\pm$ 2                  | 20000 $\pm$ 500                  | 36000   | 2.0  | 23 $\pm$ 4.6            |
| J7        | 2012 Sept 21             | 03:33                  | -115, -485                         | 135 $\pm$ 30                                 | 12 $\pm$ 1                 | 17500 $\pm$ 500                  | 15000   | 1.0  | 36 $\pm$ 7.2            |
| J8        | 2012 Sept 22             | 01:25                  | -338, 103                          | 110 $\pm$ 45                                 | 11 $\pm$ 1                 | 13000 $\pm$ 600                  | 5700  | 0.9  | 50 $\pm$ 5.1            |
| J9        | 2012 Nov 13              | 04:21                  | -28,-307                           | 55 $\pm$ 5                                   | 9 $\pm$ 3                  | 18000 $\pm$ 1000                 | 25000   | 1.7  | 34 $\pm$ 3.2            |
| J10       | 2012 Dec 13              | 10:36                  | 26, 50                             | 65 $\pm$ 20                                  | 10 $\pm$ 2                 | 9500 $\pm$ 500                   | 12500   | 1.2  | 38 $\pm$ 5.0            |





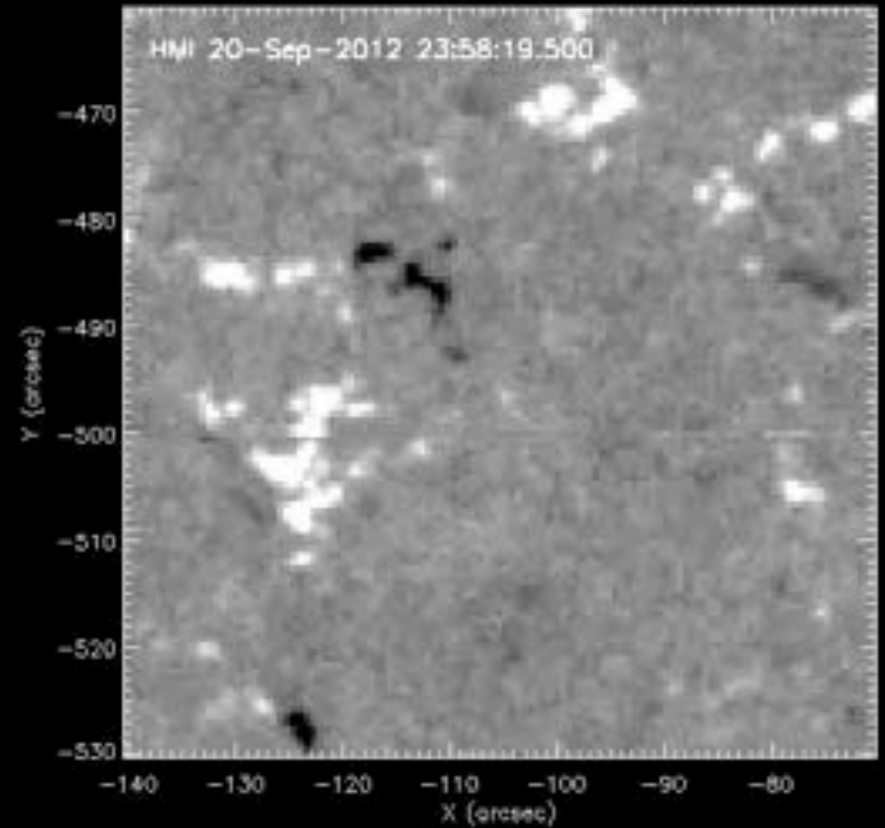
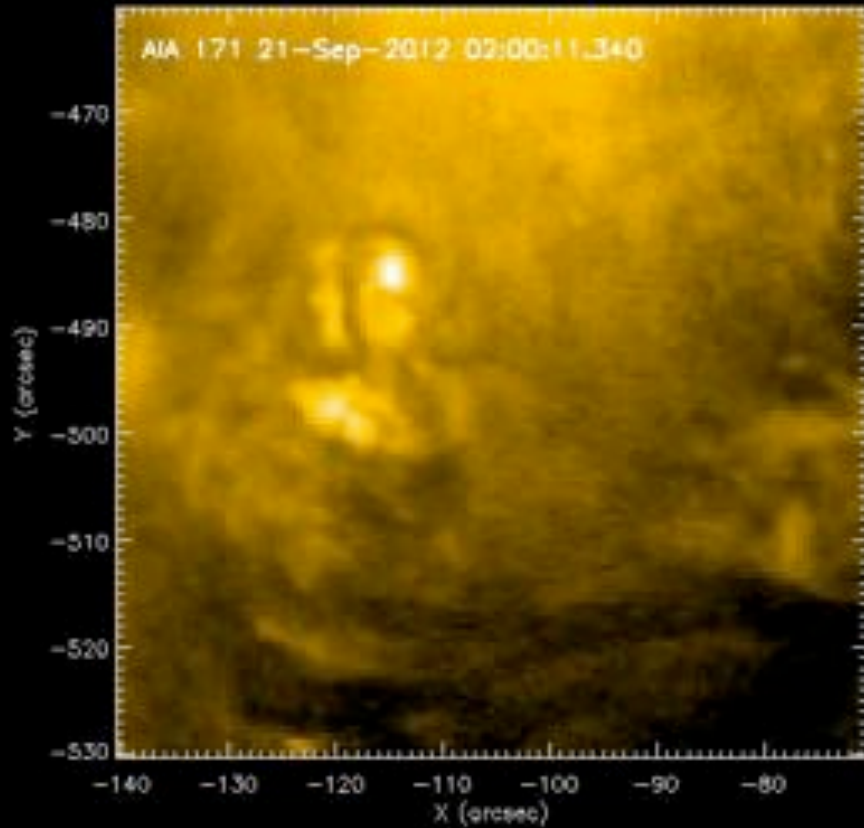
## Quiet region jet (J7)



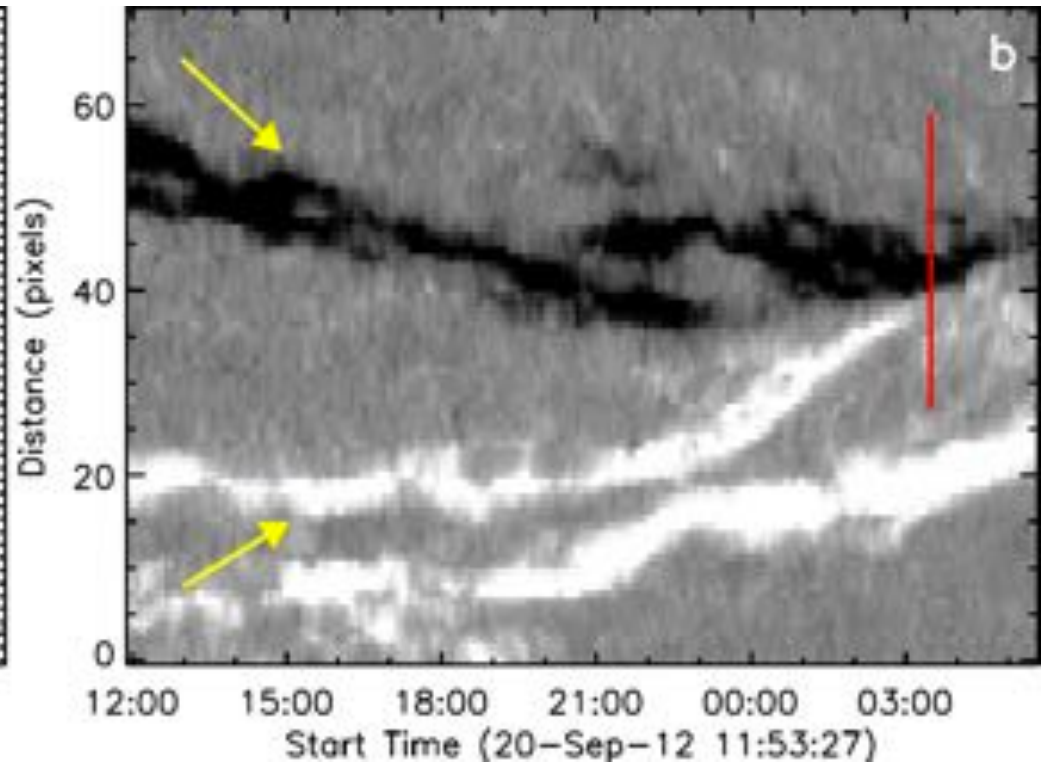
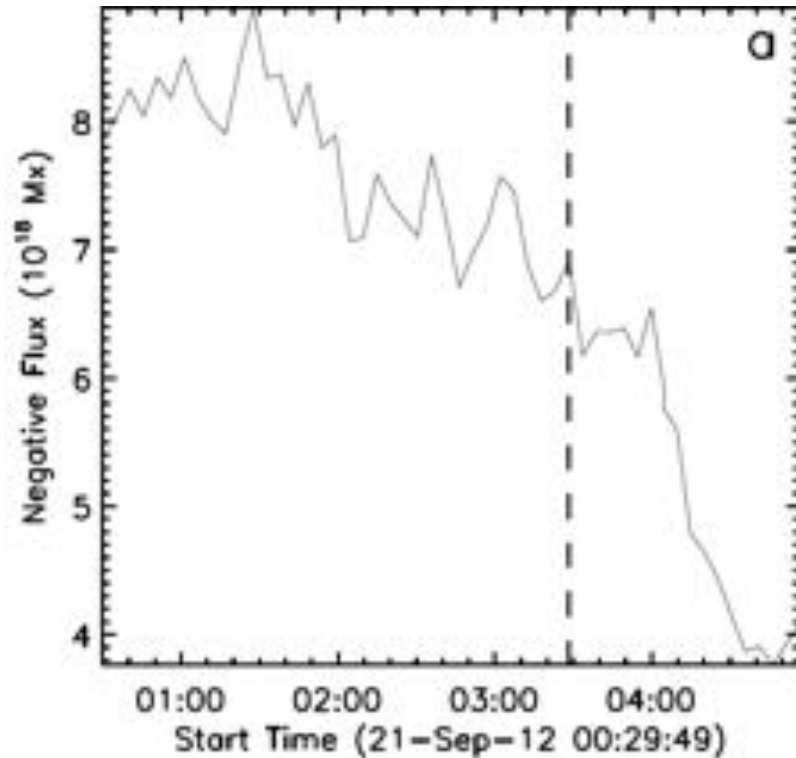
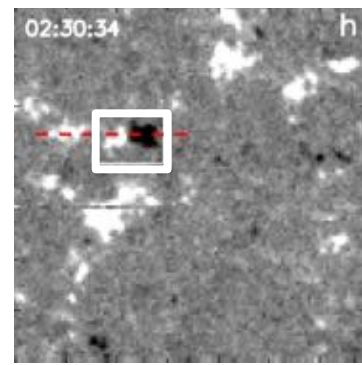
- A minifilament (length  $\sim 15000$  km) is present in the jet-base region prior to jet eruption.
- It resides over the neutral line between the opposite-polarity flux patches.
- The JBP occurs at the pre-eruption location of the minifilament.
- The jet spire extends upward with an average speed of  $135 \pm 30$  km s $^{-1}$ .



## Quiet region jet (J7)



## Flux cancellation leading to minifilament eruption



- Both polarities approach towards the neutral line, and eventually cancel with each other just before the eruption. Flux cancellation continued until the minority-polarity flux patch completely disappeared.
- We find in each of the ten jets that opposite polarity magnetic flux patches converge and cancel, with a flux reduction of 20-60 % until jet erupts.



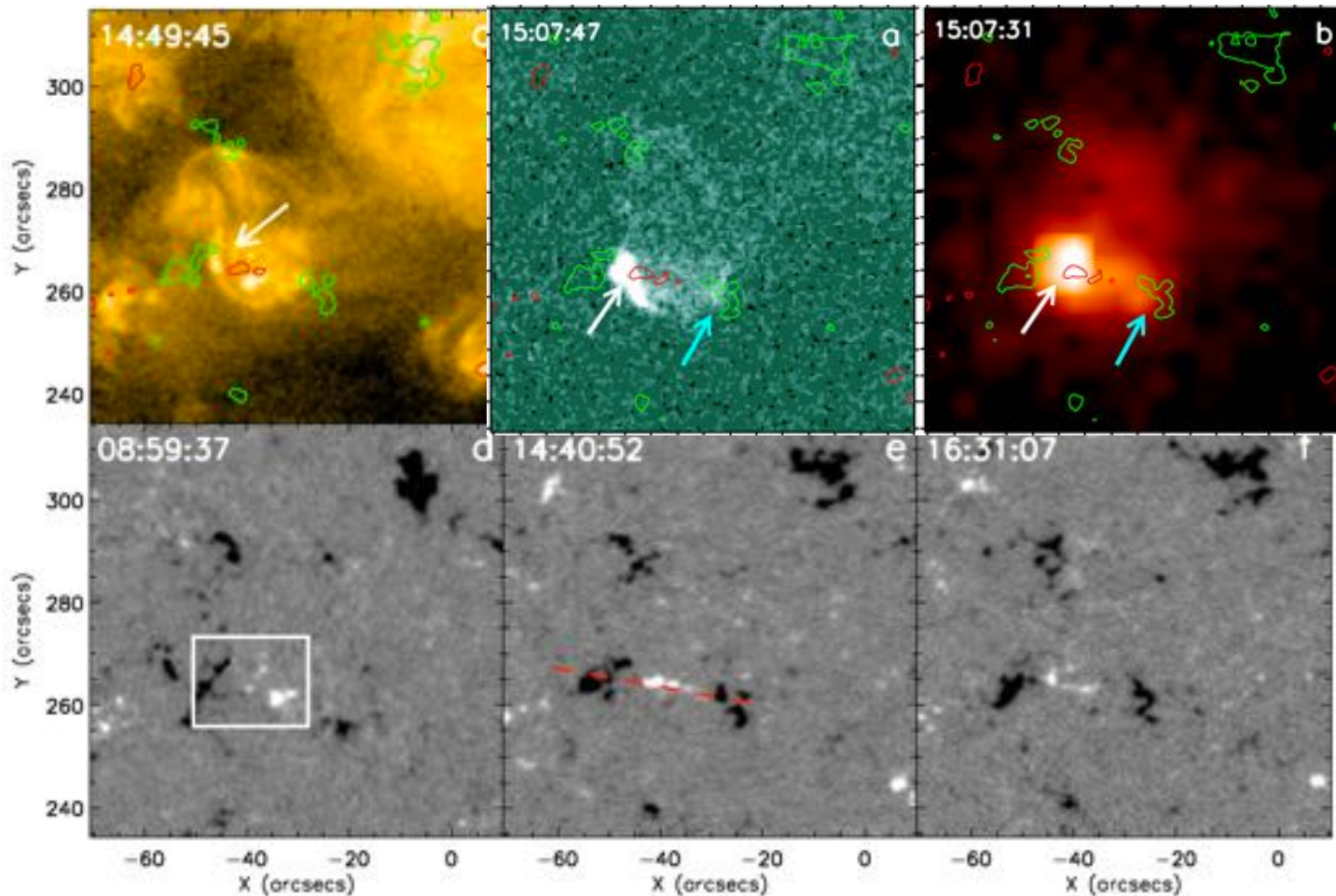


## Coronal Hole Jets

| Event No. | Date        | Time <sup>a</sup><br>(UT) | Location <sup>b</sup><br>Helio. Cord. | Jet Speed <sup>c</sup><br>(km s <sup>-1</sup> ) | Jet Dur. <sup>d</sup><br>(minutes) | Jet-Base <sup>e</sup><br>Width (km) | XRT <sup>f</sup><br>Coverage | $\Phi$ values <sup>g</sup><br>10 <sup>19</sup> Mx | % of $\Phi^h$<br>Reduction |
|-----------|-------------|---------------------------|---------------------------------------|---|------------------------------------|-------------------------------------|------------------------------|---|----------------------------|
| J1        | 2012 Jul 02 | 02:11                     | N21, W07                              | 65±1.5  | 10±2                               | 22500±1500                          | No                           | 1.5   | 33±4.5                     |
| J2        | 2015 Aug 18 | 13:07                     | N27, E02                              | 40±20   | 12±3                               | 9700±1000                           | Yes                          | 0.9   | 31±10                      |
| J3        | 2015 Dec 28 | 09:54                     | N36, E19                              | 110±40  | 7±1                                | 13000±900                           | No                           | 0.9   | 48 ±8.8                    |
| J4        | 2015 Dec 28 | 16:02                     | N37, E03                              | 35±7  | 11±1                               | 12000±2500                          | No                           | 1.2   | 52±4.8                     |
| J5        | 2015 Dec 30 | 15:14                     | N36, W23                              | 70±30   | 7±1                                | 6700±1000                           | No                           | 0.7   | 43 ±10                     |
| J6        | 2015 Dec 31 | 19:04                     | N43, W34                              | 27±4  | 6±1                                | 6600±500                            | No                           | 0.6   | 41 ±8.3                    |
| J7        | 2016 Jan 01 | 11:45                     | N08, E30                              | 30±5  | 8±1                                | 18500±3500                          | No                           | 0.7   | 52 ±6.6                    |
| J8        | 2016 Jan 01 | 18:11                     | N41, E39                              | 204±70  | 4±1                                | 1200±500                            | No                           | 0.5   | 37 ±9.8                    |
| J9        | 2016 Apr 21 | 06:15                     | S01, E12                              | 240±70  | 8±1 <sup>i</sup>                   | 10500±700                           | Yes                          | — <sup>j</sup>                                    | —                          |
| J10       | 2016 Sep 15 | 23:36                     | S06, E00                              | — <sup>k</sup>                                  | 6±1 <sup>l</sup>                   | 19000±2000                          | Yes                          | — <sup>m</sup>                                    | —                          |
| J11       | 2017 Jan 03 | 14:59                     | N20, E02                              | 105±30  | 6±1                                | 18700±6000                          | Yes                          | 1.6   | 33±5.3                     |
| J12       | 2017 Jan 04 | 09:26                     | N24, W03                              | 92±30   | 15±3                               | 9500±1000                           | Yes                          | 2.0   | 73 ±5.0                    |
| J13       | 2017 Jan 04 | 17:08                     | N19, W10                              | 103±30  | 4±1                                | 7000±500                            | Yes                          | 0.9   | 21±8.0                     |



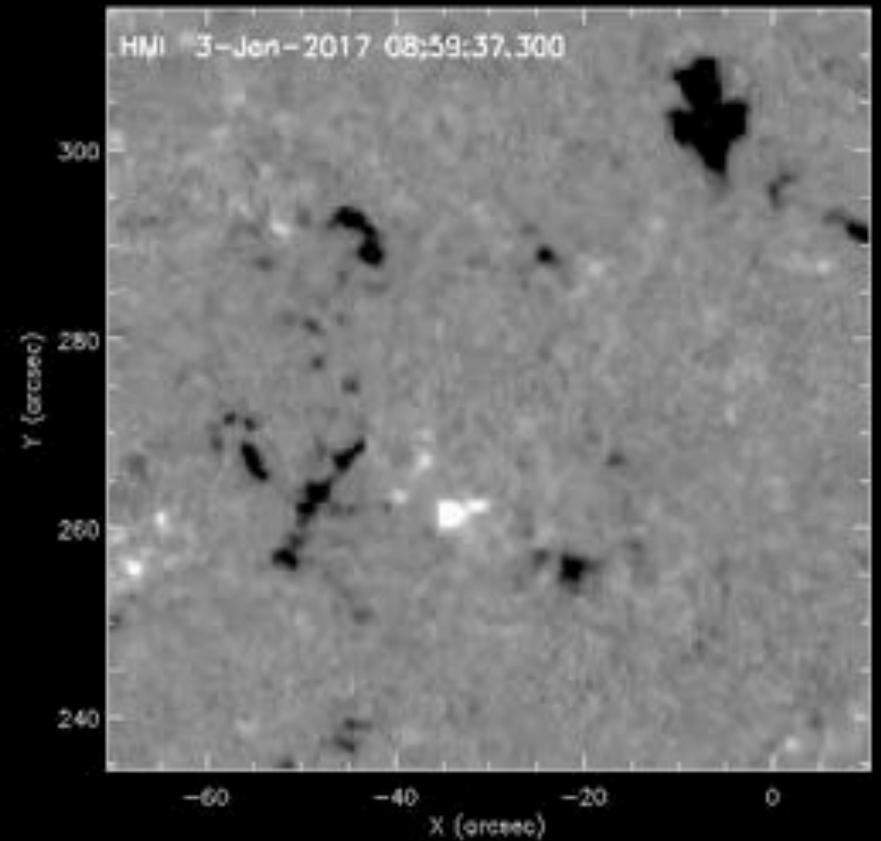
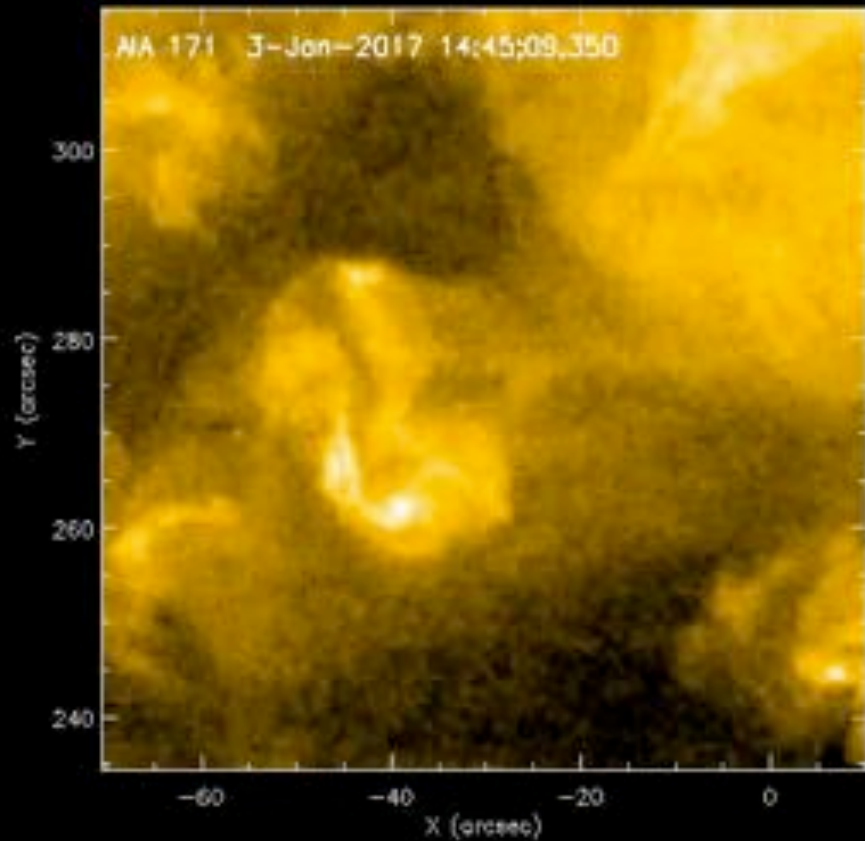
## Coronal hole jet (J11)



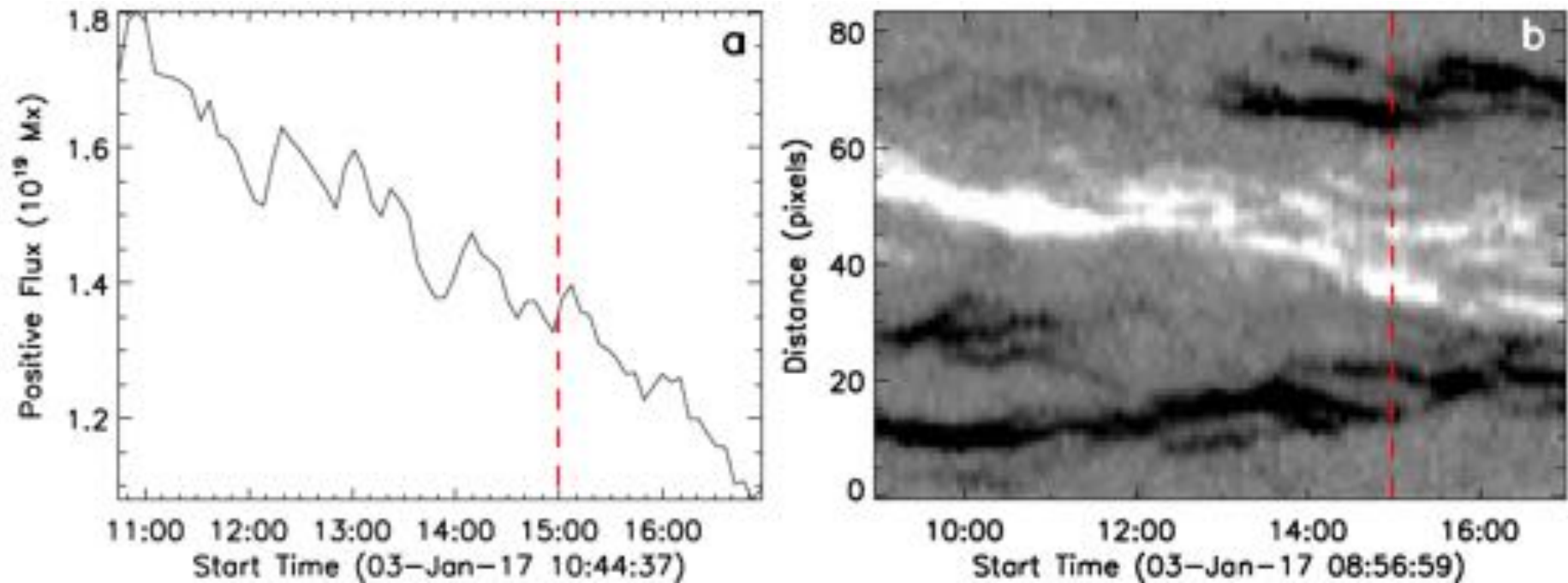
- A minifilament resides over the neutral line between the opposite-polarity flux patches.
- The JBP occurs at the pre-eruption location of the minifilament.
- The jet spire extends upward with an average speed of  $105 \pm 30 \text{ km s}^{-1}$ .



## Coronal hole jet (J11)



## Flux cancellation leading to minifilament eruption

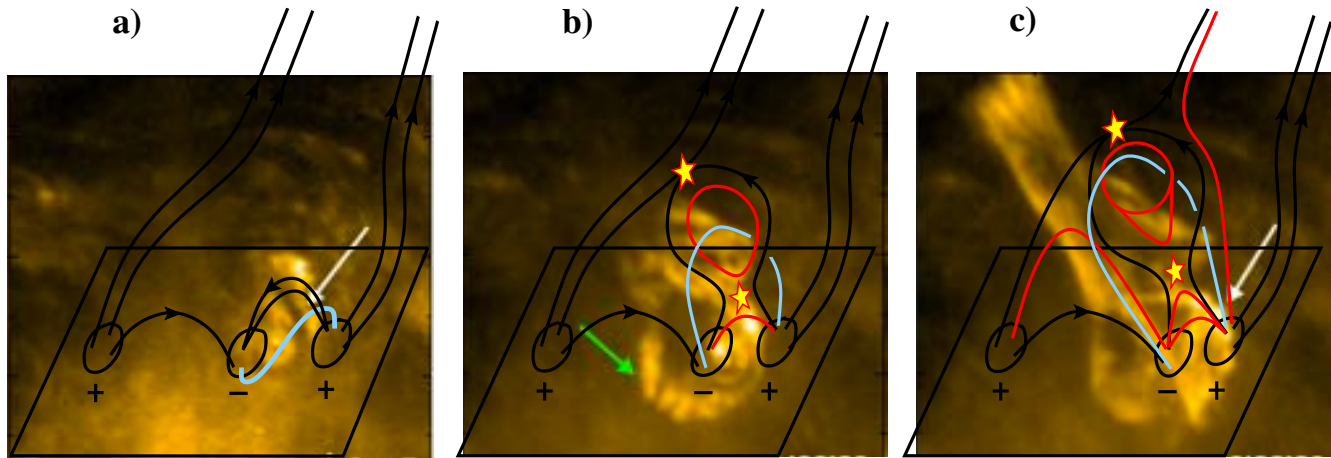


- The negative flux continuously decreases with time, which is clear evidence of flux cancellation at the neutral line of the minifilament.
- HMI time-distance map shows the convergence and cancellation of the jet-base polarities.
- We find in each of the ten jets that opposite polarity magnetic flux patches converge and cancel, with a flux reduction of 20-75 % until jet erupts.





## Schematic Illustration of Observations

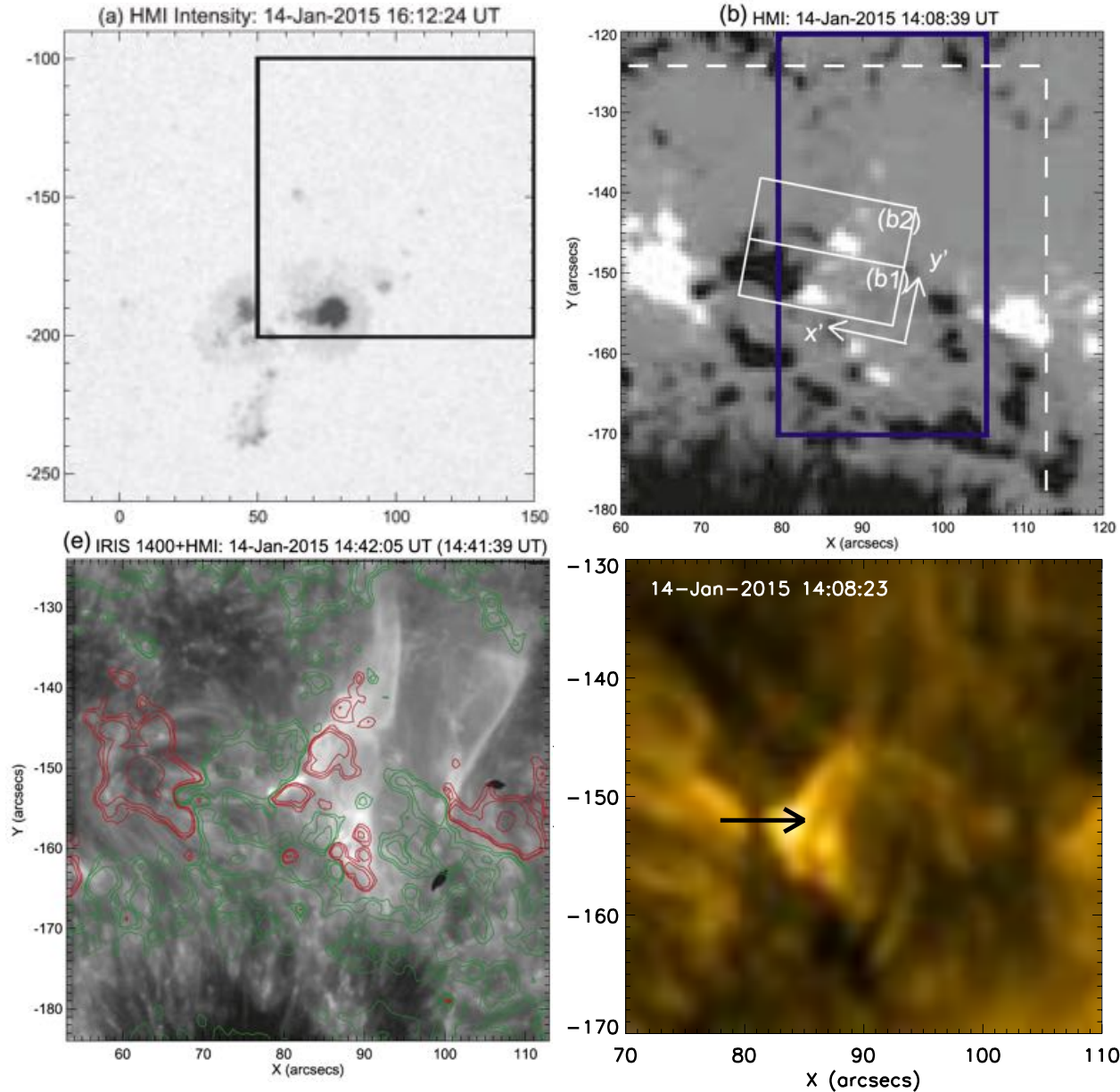


- The minifilament (blue) initially resides in sheared/twisted field between patches of majority (positive) and minority (negative) flux.
- These two flux patches converge and cancel with each other. Continuous flux cancelation at the neutral line eventually destabilizes the filament field to erupt outwards and undergo external reconnection with the surrounding coronal field.
- The external reconnection opens the erupting closed field, allowing hot reconnection-heated material and cool minifilament material to escape along the far-reaching field as the jet spire.



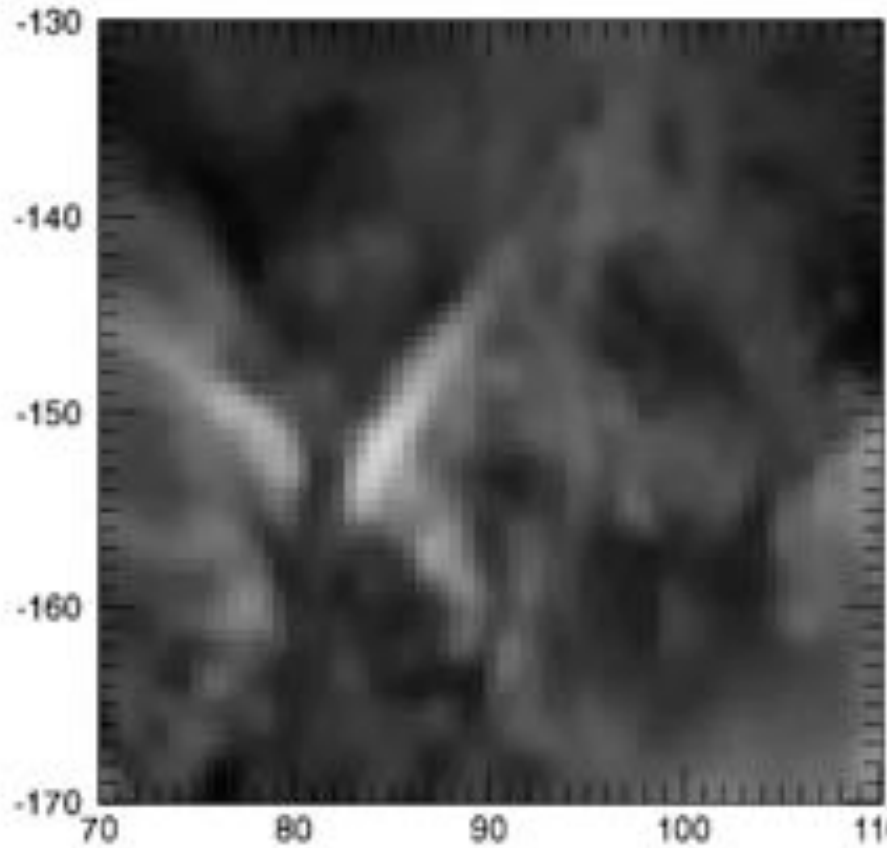


# Active Region Jets

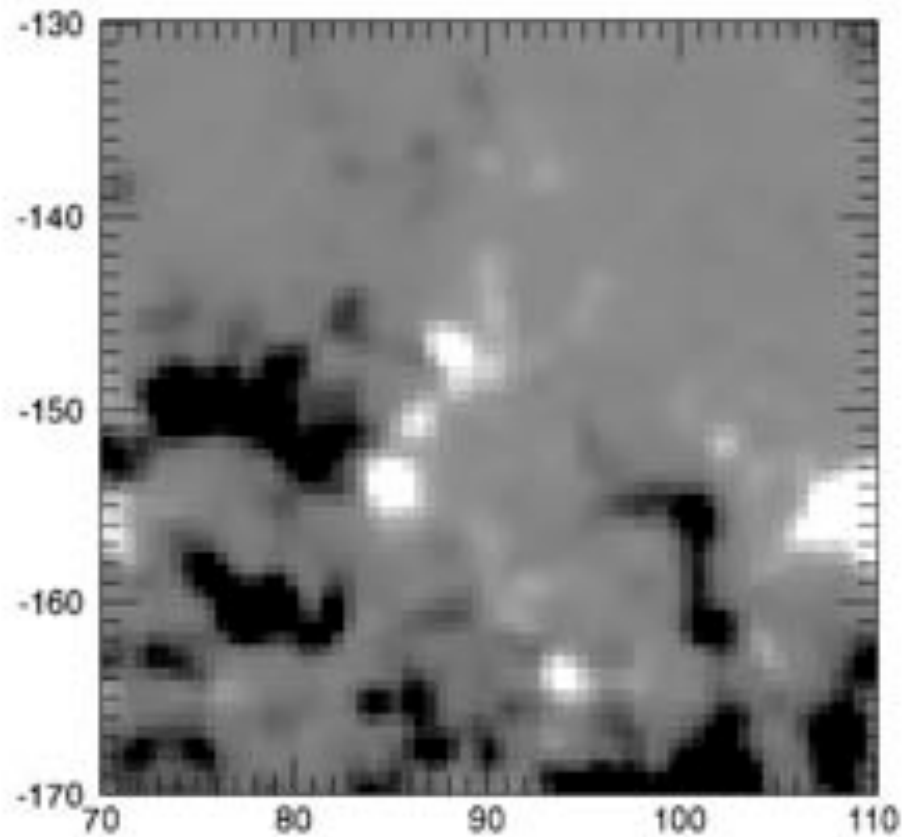


## Active Region Jet

2015-01-14 14:03:11

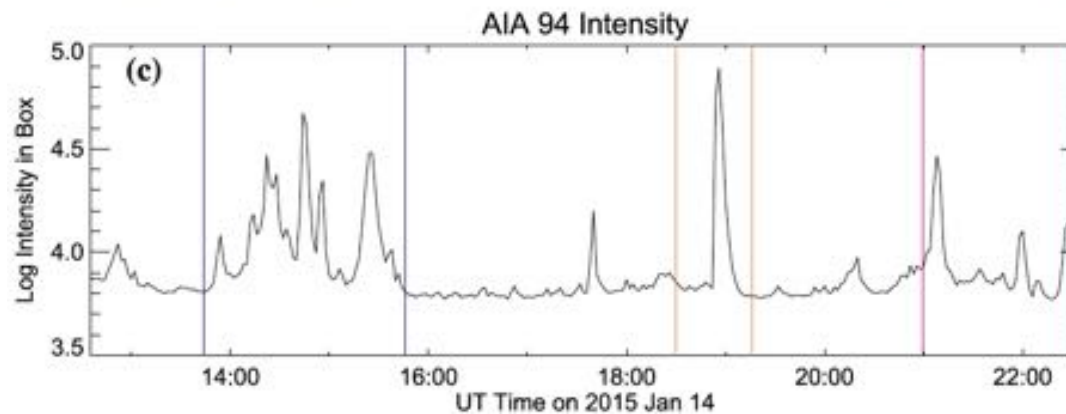
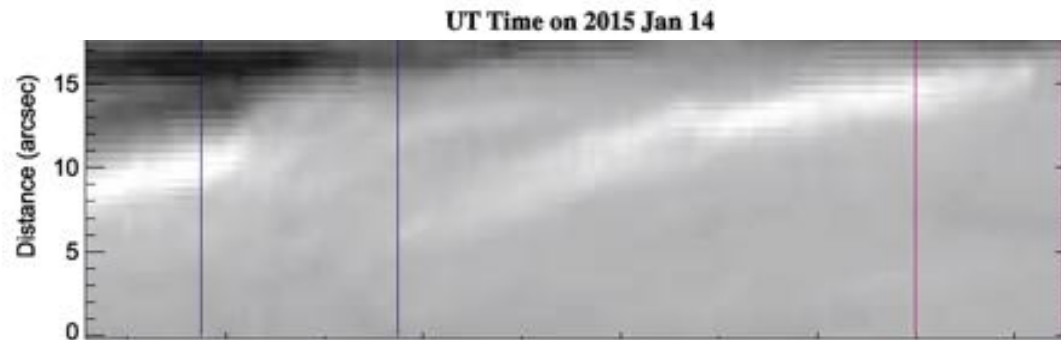
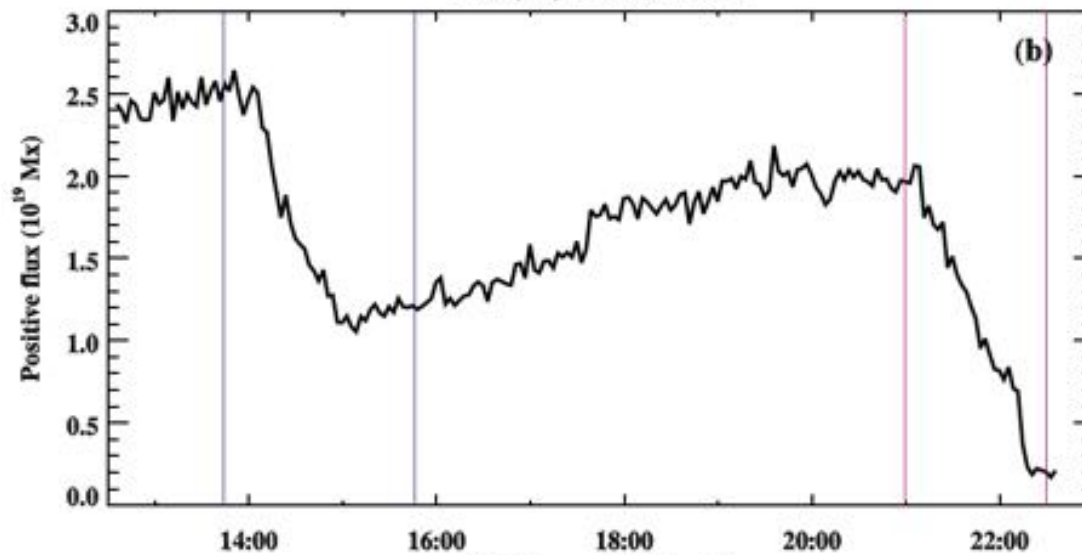


2015-01-14 13:02:39



# Flux cancellation leading to the Jet Eruption

Box (b1) Positive Flux



# **Minifilament Formation**



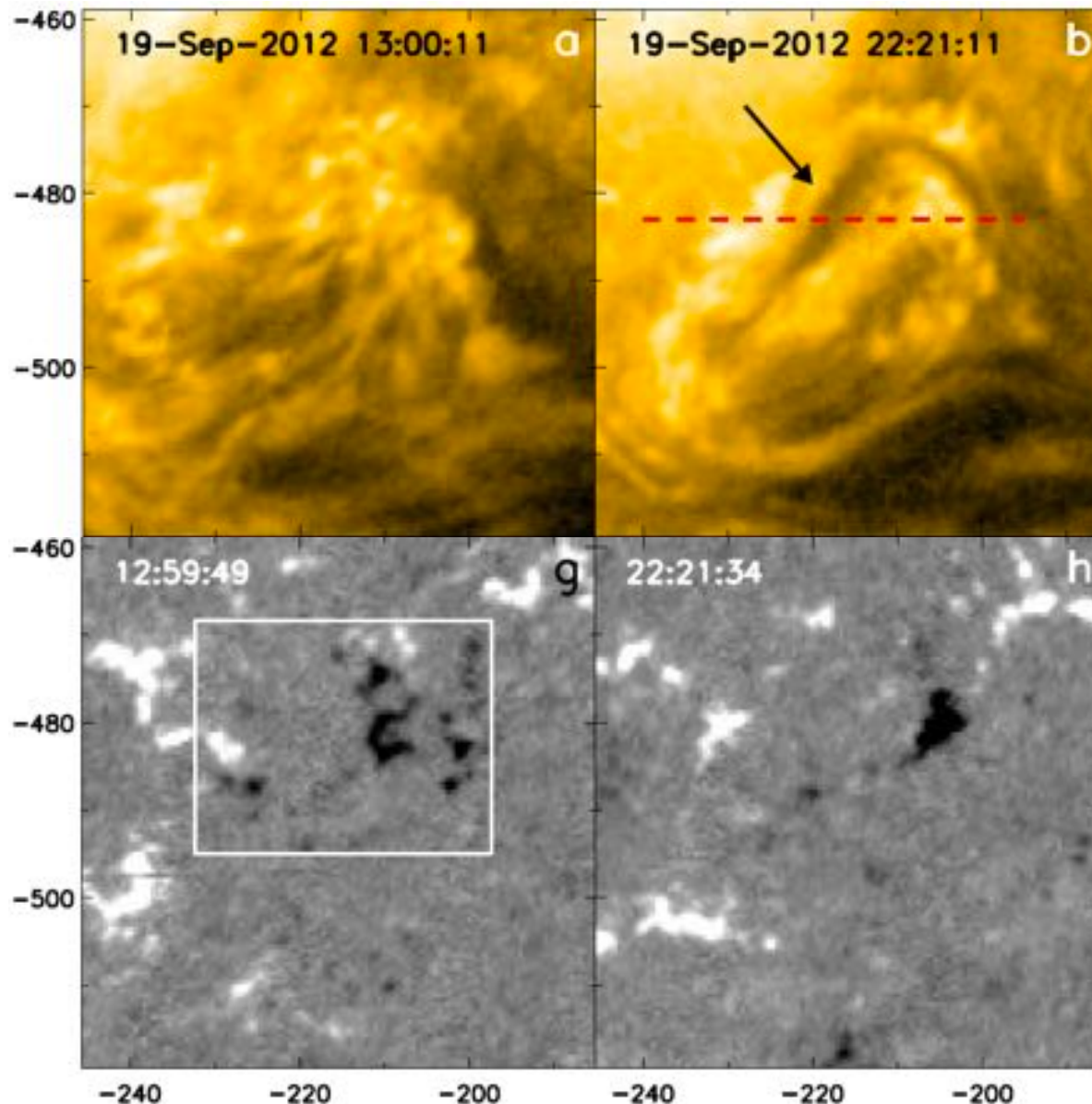
## Quiet Region Minifilament Formation

| Event No. | Minifil. formation <sup>a</sup><br>time (UT) | Minifil. eruption <sup>b</sup><br>time (UT)   | Location <sup>c</sup><br>helio. cord. | Duration of <sup>c</sup><br>minifil. (hrs) | Width of <sup>d</sup><br>minifil. (km) | No. of <sup>e</sup><br>Jets | $\Phi$ values <sup>f</sup><br>$10^{19}$ Mx | % of $\Phi$ <sup>g</sup><br>reduction |
|-----------|--|---|---------------------------------------|--|--|-----------------------------|--|---------------------------------------|
| J1        | 2012 Mar 21 22:46                            | 2012 Mar 22 04:46   | S09, E29                              | 6  | $2000 \pm 500$                         | 1                           | 1.6  | $20 \pm 6.8$                          |
| J2        | 2012 Jul 01 05:58                            | 2012 Jul 01 08:29   | N12, E02                              | 2.5  | $1500 \pm 200$                         | 1                           | $1.9^h$                                    | $20 \pm 7.3$                          |
| J3        | 2012 Jul 07 — <sup>i</sup>                   | 2012 Jul 07 21:31   | S15, E12                              | —  | $2200 \pm 200$                         | 1                           | —  | —                                     |
| J4        | 2012 Aug 04 05:14                            | 2012 Aug 05 01:58 <sup>j</sup> ,<br>2012 Aug 05 02:20                               | N07, E30                              | 21   | $2500 \pm 500$                         | 2                           | 5.8  | $14 \pm 4.6$                          |
| J5        | 2012 Aug 10 19:43                            | 2012 Aug 10 23:03   | S31, E11                              | 3.2  | $1500 \pm 200$                         | 1                           | 0.9  | $27 \pm 6.1$                          |
| J6        | 2012 Sept 19 17:15                           | 2012 Sept 20 22:52  | S34, E11                              | 34   | $2500 \pm 500$                         | 2                           | 3.0  | $9 \pm 5.3$                           |
| J7        | 2012 Sept 21 00:51                           | 2012 Sept 21 03:33  | S34, E08                              | 3.5  | $2500 \pm 500$                         | 1                           | 1.7  | $38 \pm 2.6$                          |
| J8        | 2012 Sept 21 23:55                           | 2012 Sept 22 01:25  | N01, E20                              | 1.5  | $1500 \pm 500$                         | 1                           | 0.9  | $38 \pm 5.5$                          |
| J9        | 2012 Nov 11 02:56                            | 2012 Nov 11 13:08,<br>2012 Nov 12 17:06,<br>2012 Nov 12 21:34,<br>2012 Nov 13 04:20 | S23, E01                              | 49.5                                       | $2500 \pm 500$                         | 4                           | — <sup>k</sup>                             | —                                     |
| J10       | 2012 Dec 13 08:06                            | 2012 Dec 13 10:11,<br>2012 Dec 13 10:36   | S01, W01                              | 2.5  | $1600 \pm 200$                         | 2                           | 1.2  | $7.0 \pm 8.3$                         |





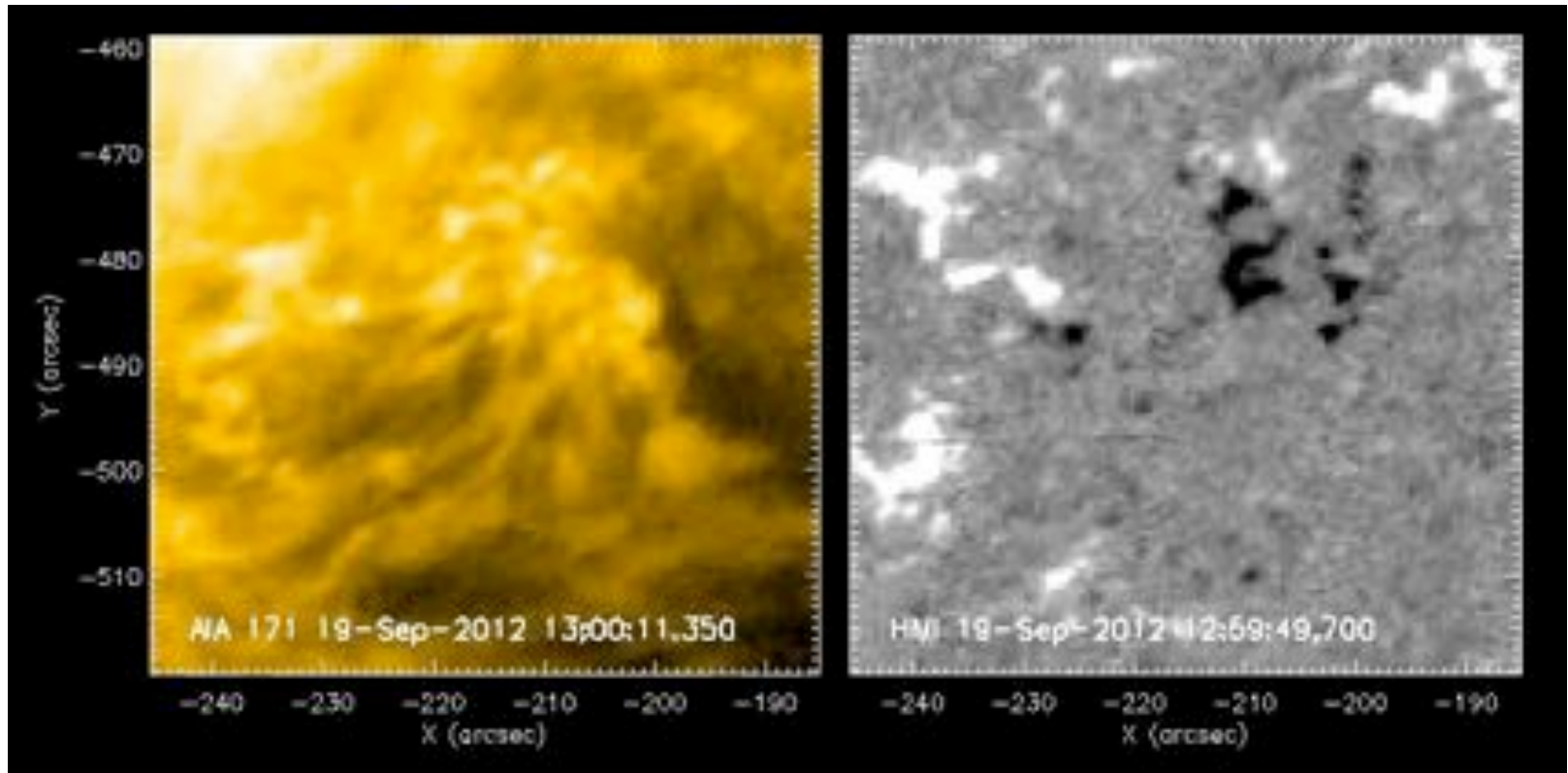
## Minifilament Formation (J7)



- Duration of minifilament ~ 38 hours
- There were two jet eruptions from the same neutral line, about 5 hour apart.



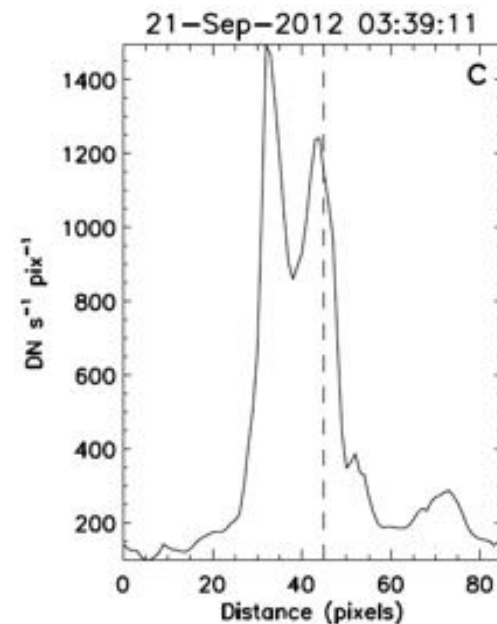
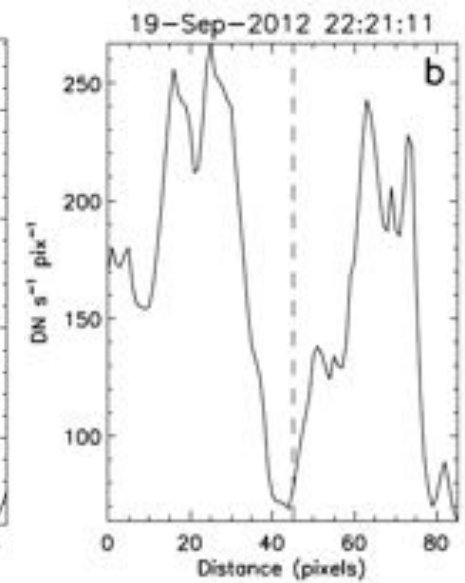
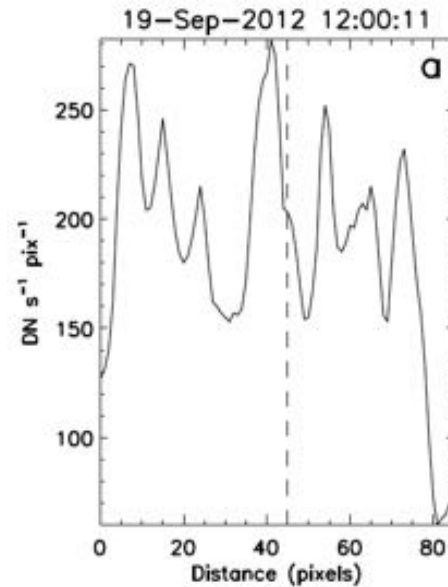
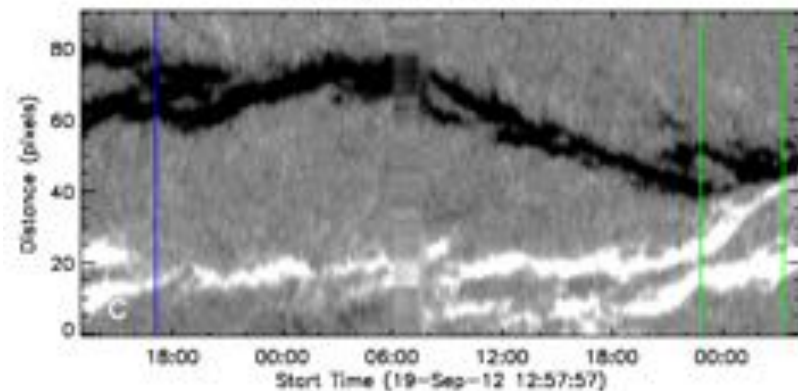
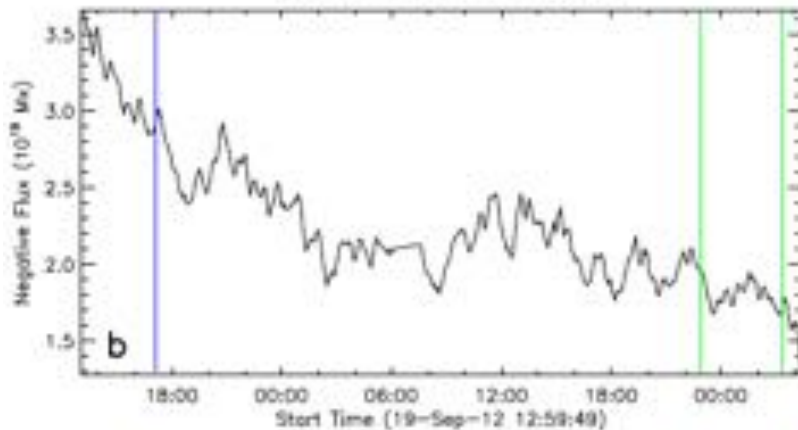
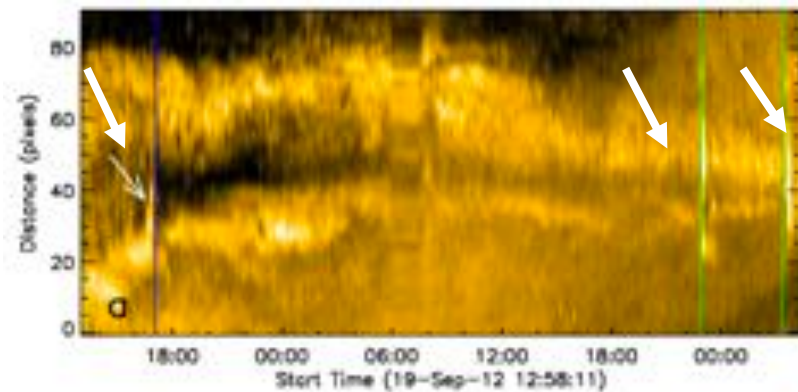
## Homologous Jet Eruptions



- We also observe more than a single jet from the same neutral line. A minifilament erupts and drives a jet, reforms/reappears at the same location, and then again erupts, driving the next jet.
- This process occurs as flux cancelation is ongoing and continues until all the minority-polarity flux vanishes.



# Minifilament Formation and Flux Cancellation



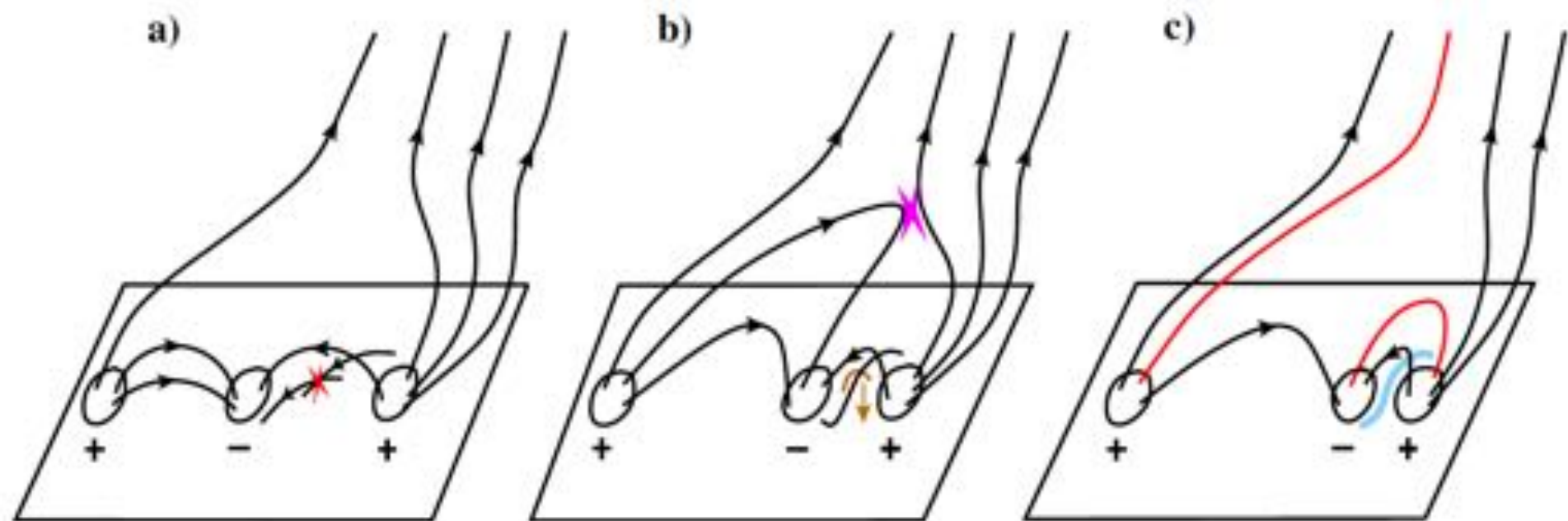
## Origin of Minority-Polarity Flux Patch

We found the three scenarios:

- In some events tiny grains of flux coalesce to make a minority-polarity flux clump.
- The minority-polarity foot of a newly-emerged bipole became the minority-polarity flux patch.
- In some cases the minority-polarity clump preexisted as it rooted onto the Earthward side of the Sun 2-3 days before our observations began.

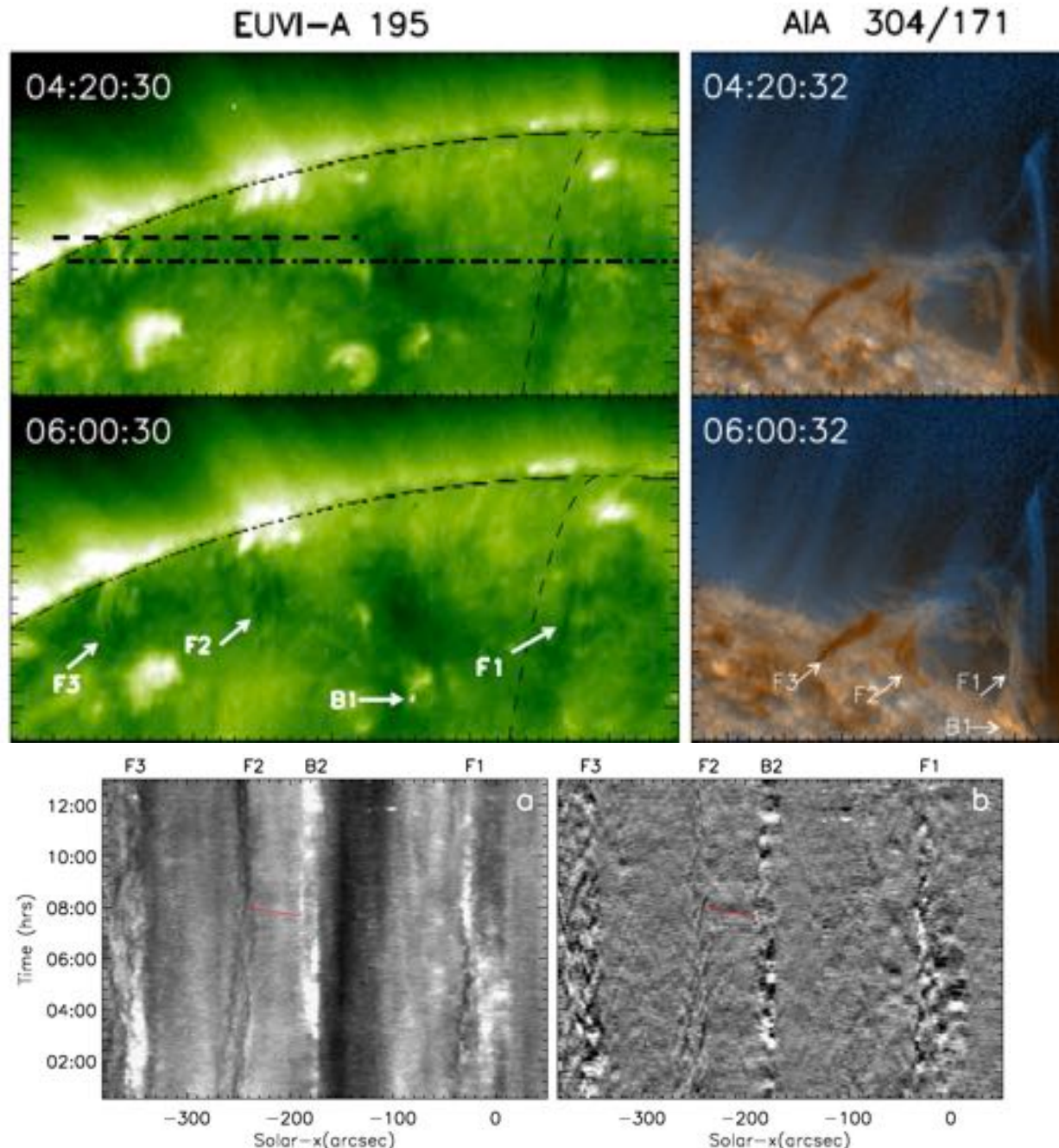


## Schematic Illustration of Observations

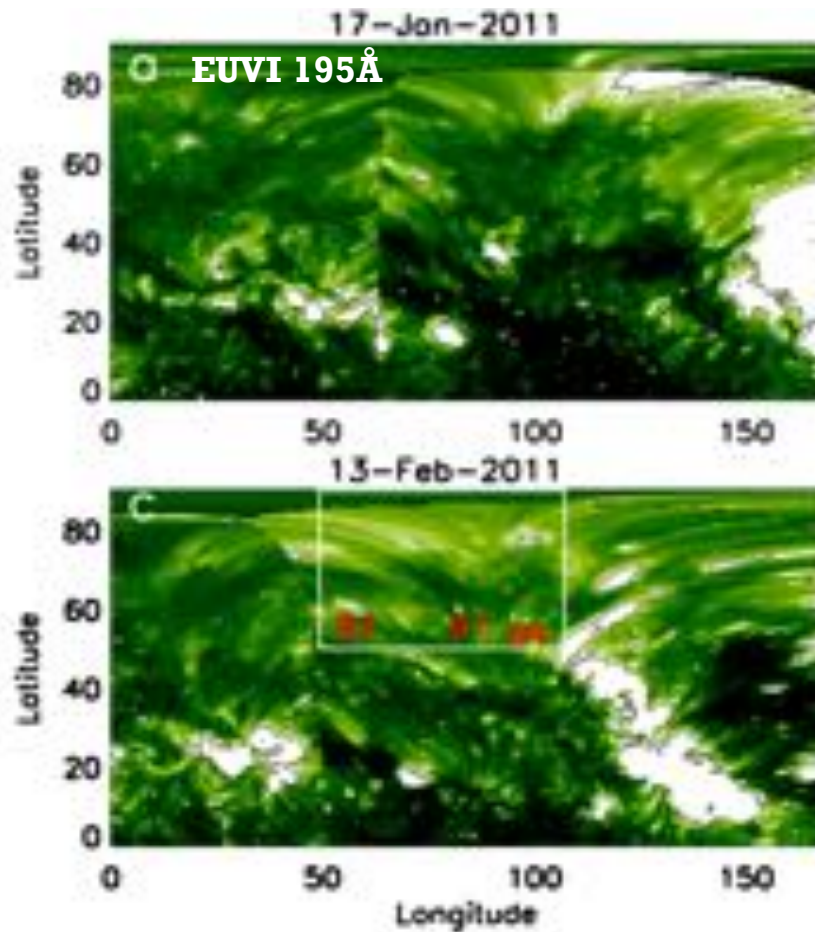




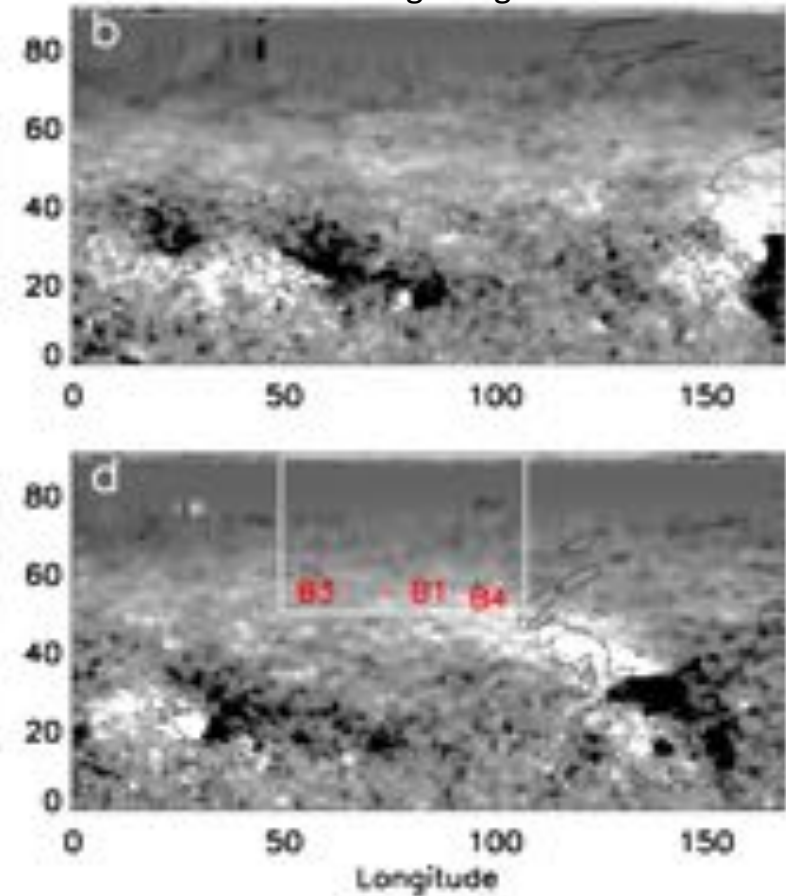
# Polar Crown Prominence Observed on 13 Feb 2011



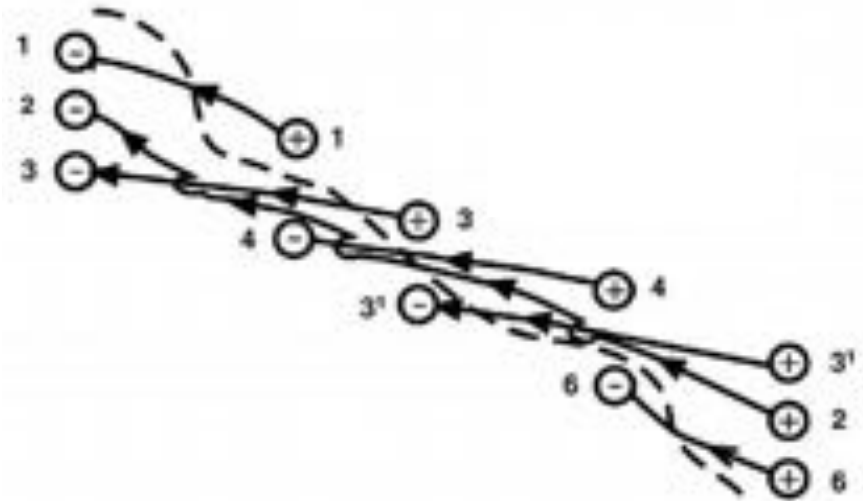
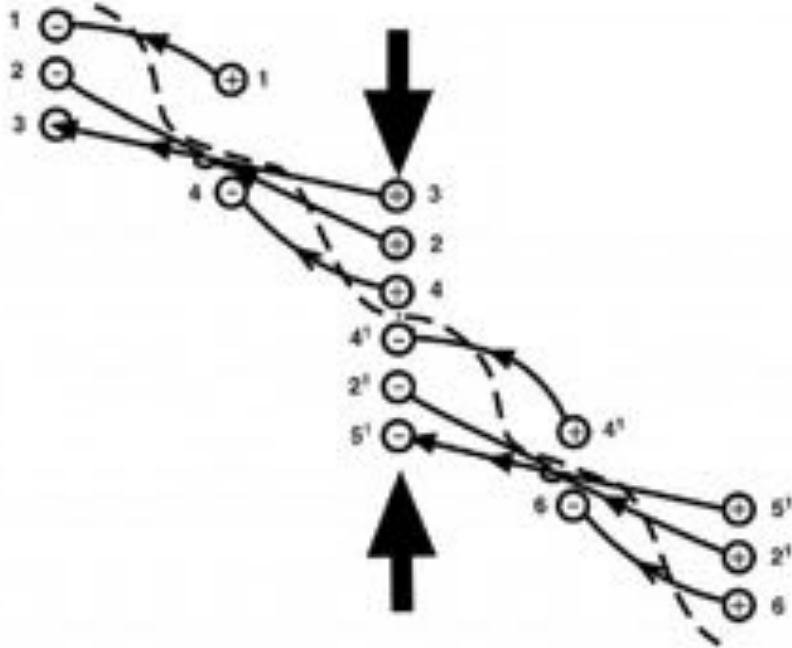
## Magnetic Field Structure



GONG magnetogram



## Flux Linkage Model



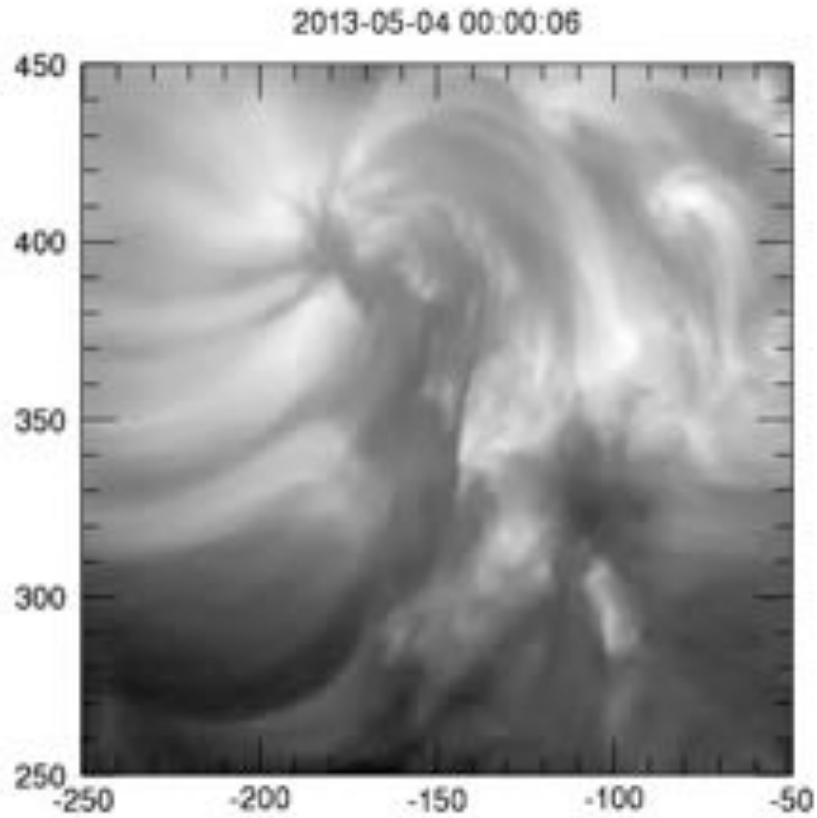
- The interaction between two unconnected bi-poles, one is older and diffused which is at higher latitude, the other polarity is at lower latitude.
- This results in the highly sheared field at the PIL. Thus, after the many repetitions of this process, it forms the long helical structures that can partly or fully cover the polar region of the Sun.



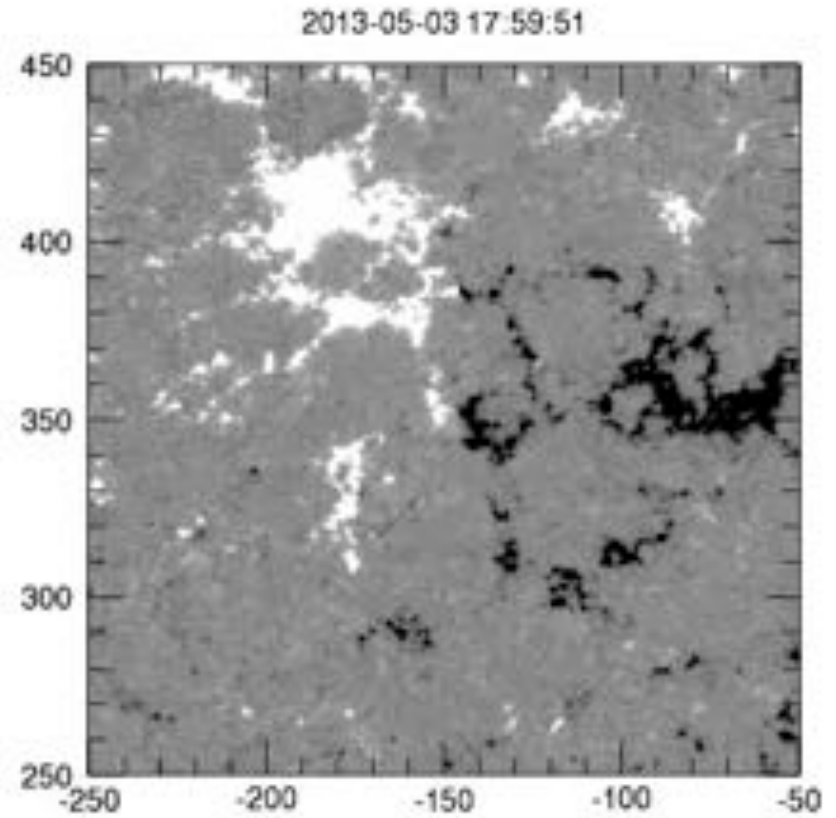
# **CME-producing Filament Eruptions**



## Filament Observed on 04 May 2013



**AIA 193 movie**

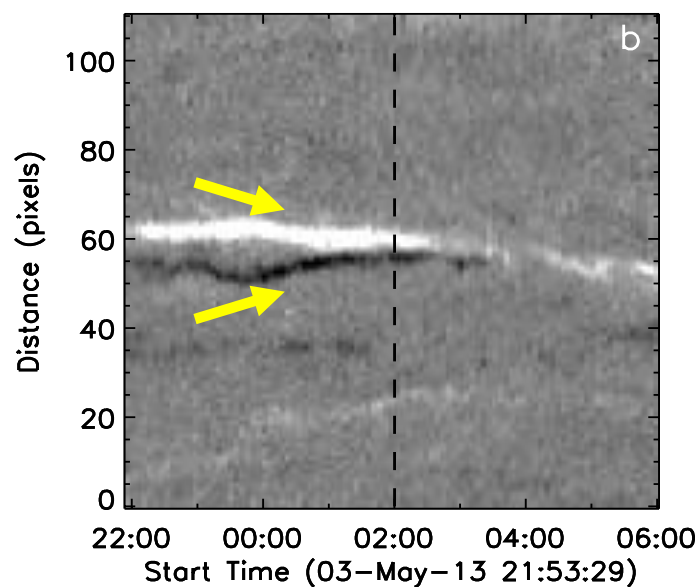
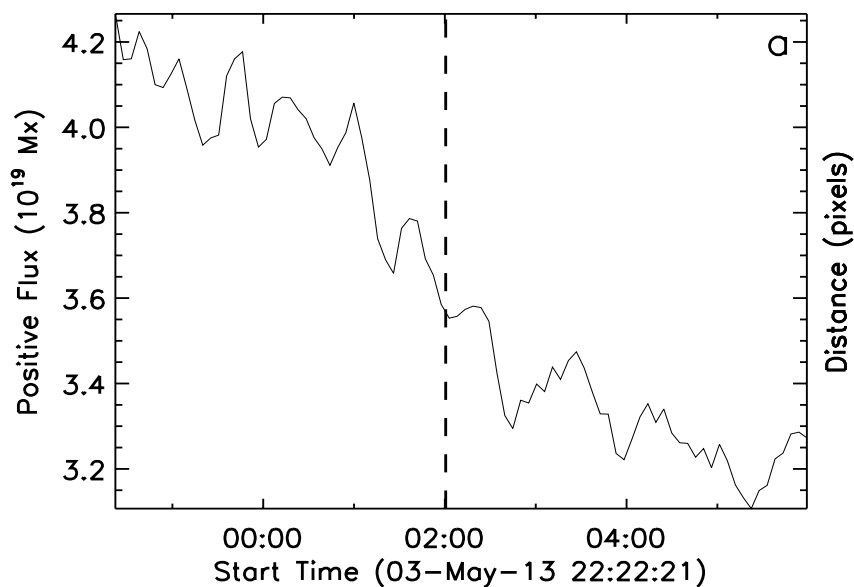
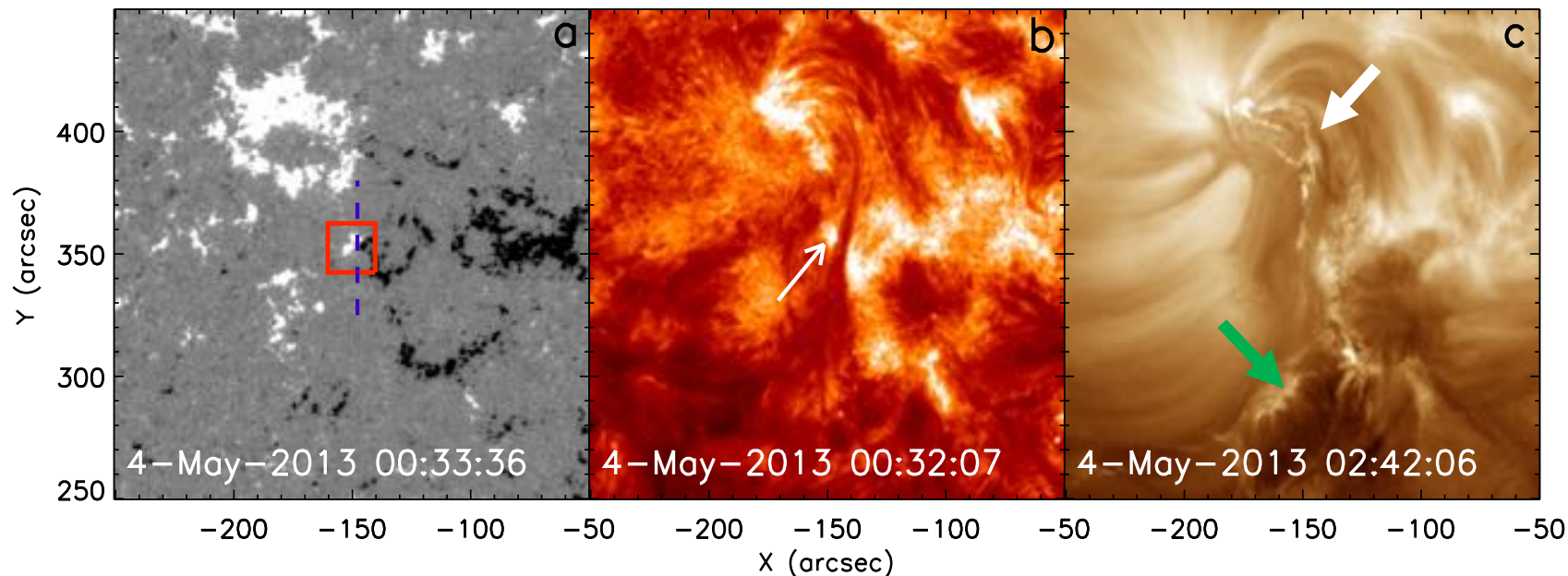


**HMI Magnetogram movie**

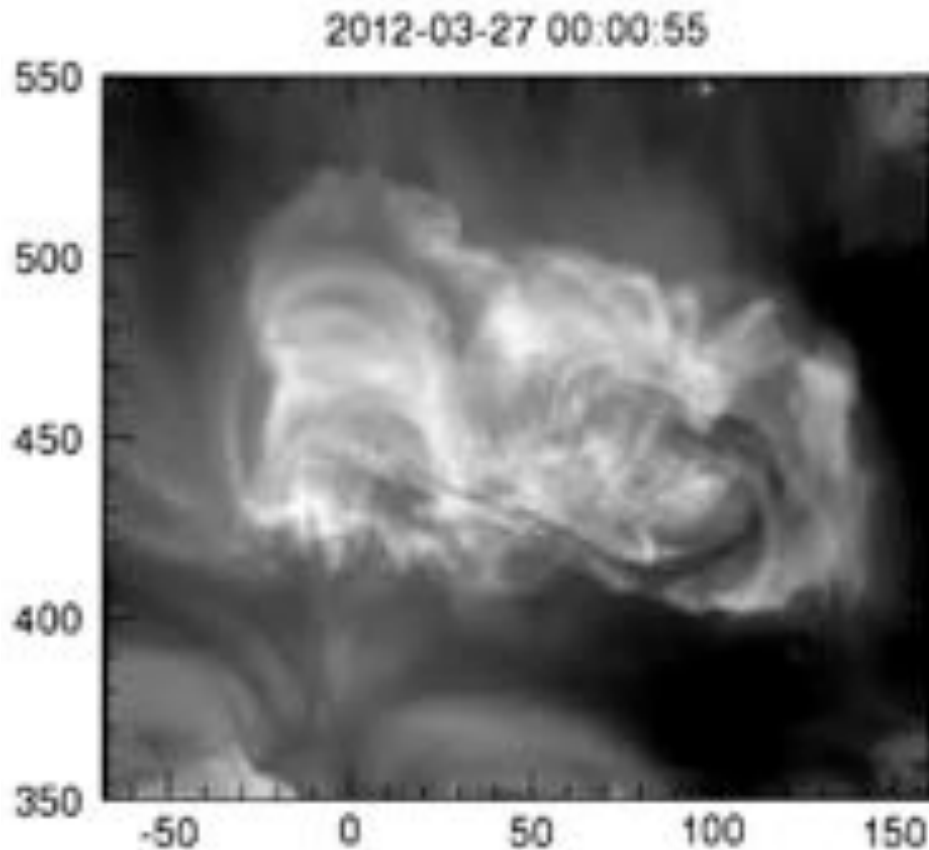




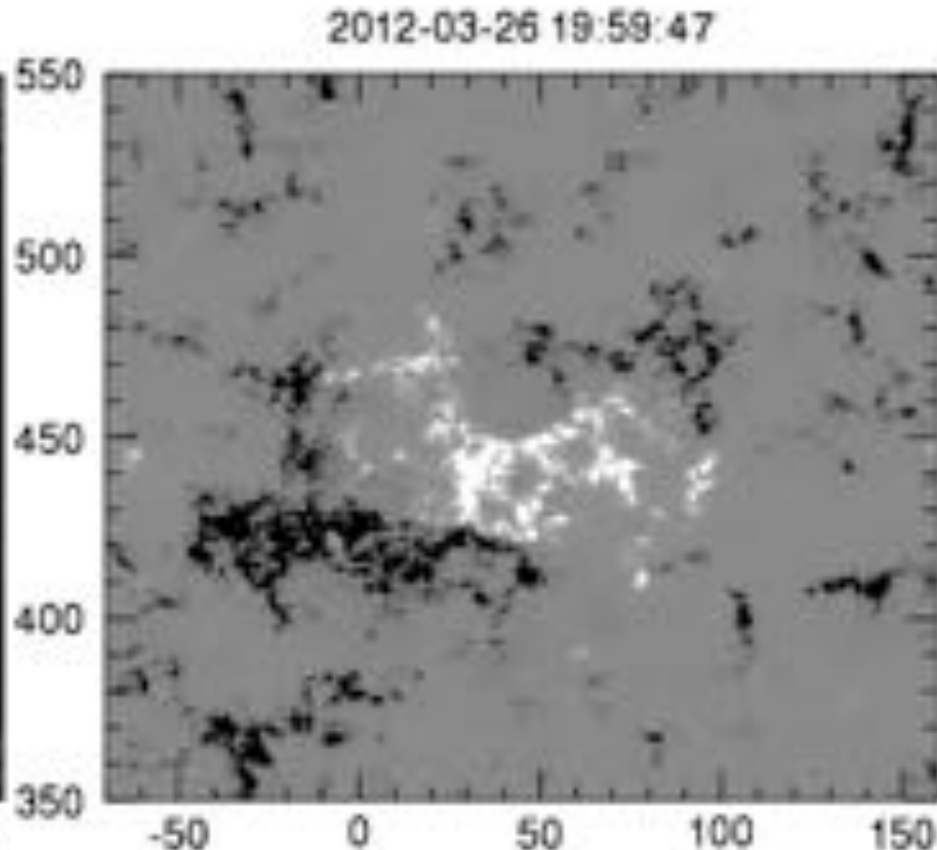
## Flux Cancellation at the Neutral line



## Filament Observed on 27 March 2012



**AIA 193 movie**



**HMI Magnetogram movie**

- Continuous flux cancelation at the neutral line of the filaments often triggers their eruptions. This corresponds to the finding that persistent flux cancelation at the neutral is the cause of jet-producing minifilament eruptions.
- Thus our observations support coronal jets being miniature versions of CMEs.



## Summary

- We examined in detail random on-disk quiet-region jets and coronal hole jets.
- In each event a cool-transition-region material, a minifilament, initially resides at a neutral line inside the jet-base region.
- Our observations suggest that flux cancelation is usually the trigger of quiet-region and coronal hole jet eruptions.
- We found that flux cancelation is the key agent responsible for building a highly sheared minifilament field, leading to the formation of minifilaments.
- All the jet-producing eruptions are similar to typical solar flare eruptions, where a solar flare arcade forms during the filament eruption along the neutral line along which the filament resided prior to its eruption.

